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4-layer Nb_3Sn Quadrupole Coil in MQXB Collar

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Introduction

Fermilab is studying the large-aperture high-gradient quadrupole magnets for the future LHC luminosity upgrade and possible other applications. Designs of 90, 100 and 110 mm quadrupole magnets with the nominal field gradient of 205 T/m, based on the Nb_3Sn conductor and shell-type coil are being analyzed [1,2]. The design of 90 mm magnet is based on 2-layer coil and the design of 100 and 110 mm magnets is based on 4-layer coils.

In order to simplify the initial steps of the LHC IR quadrupole short model R&D program it is anticipated to start from the 70 mm Nb_3Sn models that would utilize the existing MQXB collar structure and iron yoke. A usage of the available stainless steel collars along with the assembly tooling would accelerate the model development and manufacturing and reduce the program cost. In addition, such magnets could be used in Tevatron's new or upgraded IRs.

The quadrupole design fitting inside the MQXB collars based on 2-layer shell-type coil has been developed and described in [3]. This note presents the design and parameters of the 70-mm 4-layer quadrupole magnet in the MQXB collars developed using similar constraints as the 2-layer design. A comparison between 2-layer and 4-layer designs is also presented.

1. Coil optimization

The major constrain for the coil design was the requirement to fit inside the MQXB collar [4]. All 4 layers were made from the same cable with the width equal to the half cable width in the original 70-mm design.

The coil was optimized using ROXIE code [5] with constant permeability of the iron yoke of 3000 and the yoke inner radius of 92.564 mm, corresponding to the MQXB yoke inner radius. The insulated turns of the inner layer were aligned on the inner mandrel surface with 35.00 mm radius and turns of the outer layer were aligned on the outer mandrel with the radius of 66.63 mm (assuming the ground insulation thickness of 0.52 mm).

Thickness of the ground insulation between the collar and pole turns was the same as in MQXB design. There were also additional shims, necessary to fill the gaps between the coil pole turns and the collar. Thickness of the interlayer insulation, predetermined by the radii of the mandrels and the cable size, was 0.54 mm.

Figure 1 presents one octant of the optimized coil cross-section within the MQXB collar. In order to accommodate the maximum number of turns and achieve the best field quality, the cable insulation thickness (per side) was reduced from 0.180 mm to 0.170 mm. The cable parameters are summarized in Table 1.

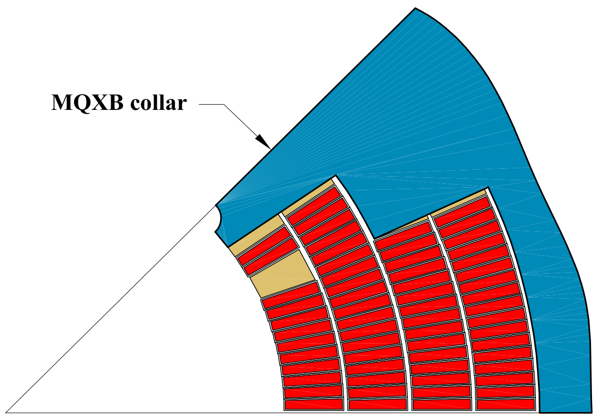

Fig. 1. 4-layer coil within the MQXB collar.

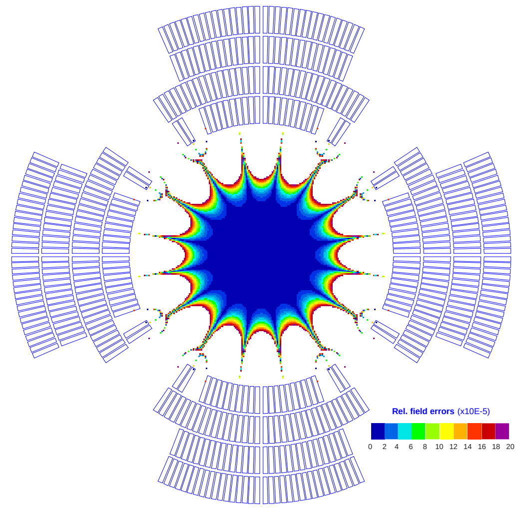

Fig. 2. Field quality in the coil aperture.

Table 1. Cable parameters.

Parameter	Unit	Value
Number of strands	-	20
Strand diameter	mm	0.7
Bare width	mm	7.184
Bare inner edge thickness	mm	1.148
Bare outer edge thickness	mm	1.323
Cabling angle	degree	14.5
Keystone angle	degree	1.4
Average packing factor	%	89.0
Inner edge compression	%	18.0
Outer edge compression	%	5.5
Width compression	%	0.0
Radial insulation thickness	mm	0.17
Azimuthal insulation thickness	mm	0.17
Copper to non-copper ratio	-	1.2

The field quality for the optimized 4-layer coil cross-section is presented in Figure 2 and Table 2. As it can be seen from the data in Table 2, b_6 component in all the designs is almost the same. The higher order allowed components b_{10} and b_{14} in both 4-layer and 2-layer designs are much larger than in original MQXB since they could not be minimized in the given collar design.

Table 2. Field harmonics at 17 mm reference radius (10^{-4}).

Harmonic	4-layer design	2-layer design	MQXB
b_6	0.0172	0.0070	-0.013
b_{10}	-0.4479	-0.4910	-0.001
b_{14}	-0.0142	-0.0061	-0.0011

It is acceptable at this stage, since the main goal of this quadrupole model is investigation of the fabrication technology, the magnet mechanical and quench performance rather than tuning the field quality. Final tuning of systematic field components may be done later by varying the midplane insulation thickness after analysis of the collar and yoke magnetization effects, and other systematic field distortions.

2. Magnet parameters

The major magnet parameters for both 4-layer and 2-layer designs are summarized in Table 3. The magnet quench parameters were calculated for the critical current density in the coil non-copper area of 2000 A/mm^2 at 12 T and 4.2 K (no I_c degradation was assumed).

Table 3. Quadrupole magnet parameters.

Parameter		4-layer design	2-layer design
Aperture, mm		70	70
Turns per quadrant		62	29
Quench gradient G @ 4.2K, T/m		280.0	292.5
Quench current I@ 4.2K, kA		7.60	16.430
Transfer function G/I, T/m/kA		36.84	17.801
Stored energy W @ quench, kJ/m		394.79	413.9
Inductance, mH/m		13.67	3.07
Quench forces per first coil octant, MN/m	F_x	1.53	1.56
	F_y	-1.93	-2.03

The maximum calculated field gradient for the 4-layer design is about 280 T/m that is 10 T/m less than for the 2-layer design. It is due to larger fraction of insulation in practically the same coil cross-section in spite of a smaller wedge in the 4-layer design. Inductance of the 4-layer design is a factor of four larger than that of the 2-layer design due to a factor of two larger number of turns, but the stored energy and Lorentz forces are approximately the same in both designs.

3. Conclusions

The maximum calculated field gradient for both 4-layer and 2-layer designs at 4.2 K operation temperature is about 280-290 T/m for commercially available Nb_3Sn strands with J_c(12T,4.2K)~2-2.2 kA/mm^2. The maximum field gradient of these Nb_3Sn magnets at 4.2 K is 12-16% higher than the maximum field gradient of the NbTi MQXB magnet at 1.9 K. Using the R&D Nb_3Sn strands with J_c(12T,4.2K)~2.9-3.0 kA/mm^2, maximum gradient increases by ~10%. An additional increase of the gradient can be achieved in the 4-layer design by cable grading in the coil, compensating lower efficiency of this design with respect to the 2-layer design. The 4-layer design is more complicated but seems more attractive for Tevatron IRs due to lower operation current. Field quality tuning is also possible by simultaneous collar optimization that will be done if necessary.

References

[1] A.V. Zlobin, G. Ambrosio, N. Andreev, P. Bauer, D. Chichili, Y. Huang, L. Imbasciati, V.V. Kashikhin, M. Lamm, P. Limon, I. Novitski, T. Peterson, J.B. Strait, S. Yadav, R. Yamada, "Conceptual design study of Nb3Sn low-beta quadrupoles for 2nd generation LHC IRs", Proceedings of 2002 Applied Superconductivity Conference, August 2002.

[2] V.V. Kashikhin, A.V. Zlobin, "Aperture limitations of 2nd generation IR quadrupoles for the LHC luminosity upgrade", TD note TD-03-003.

[3] V.V. Kashikhin, A.V. Zlobin, "Nb_3Sn Quadrupole Coil in MQXB Collar", TD note TD-02-012.

[4] FNAL drawings: 5520-ME-369190, 5520-MC-369189.

[5] S. Russenschuck, "ROXIE – the Routine for the Optimization of magnets X-sections, Inverse field computation and coil End design", Proceedings of the First International ROXIE Users Meeting and Workshop, CERN, Geneva, Switzerland, 1998, CERN-99-01, pp.1-5.